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"Agility" – Complexity Description in a New Dimension applied for Laser Cutting

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Abstract

How to describe or to compare the complexity of industrial upcoming part geometries in laser-cutting? This question is essential for defining machine dynamics or kinematic structures for efficient use of the technological cutting-potential which is given by modern beam sources. Solid-state lasers as well as CO_2 lasers offer, especially in thin materials, the opportunity of high cutting velocities. Considering the mean velocity on cutting geometries, it is significantly below the technological limitations. The characterization of cutting geometries by means of the agility as well as the application for laser-cutting will be introduced. The identification of efficient dynamic constellations will be shown as basic principle for designing future machine structures.

Keywords: agility; Wendigkeit; complexity; machine-dynamic; laser-cutting; high-dynamic

1. Motivation

The main motivation is to provide a specification-form of complexity in the face of cutting machines. With a specification-form typical spectra of part-complexity according to material thickness or industrial sectors can be defined. The identification of efficient machine dynamics to fulfil the technological limitations could be achieved with the knowledge of upcoming part complexities.

In the proceedings of [1] the problem of defining the length of coastlines (according to their roughness/ complexity) by the fractal dimension is presented. This is the single approach in complexity description of 2D paths which can be found in the literature. However the fractal dimension is not applicable to the present task, due to the geometric character of cutting-parts. The fractal dimension of two-dimensional geometries is equal to the geometric dimension. All two-dimensional cutting-geometries have the fractal dimension of two. Coast-lines or boarder-lines are real fractals which generate new structures by magnification. Dimension-values between one and two are characteristically for fractals.

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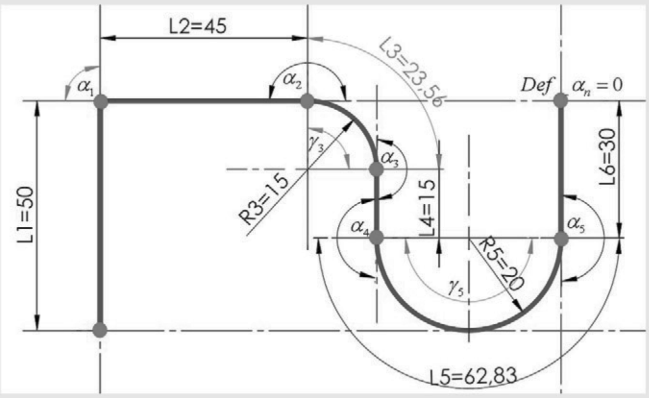
A new characterization form is required for describing the complexity of cutting-part geometries with a simple value, like the fractal dimension.

2. Solution – Complexity description by means of the "agility"

In the present paper the specification of part complexity by ratio of angle and length is proposed. Regarding all angle changes on a path which are necessary for generating a part, divided by the complete path length. All cutting- and positioning- movements are comparably observed. The calculation of the agility is a batch bulk process by using the standard NC machine code (G-Code). Each section of the code is analyzed for its length and angle compared to the previous one. The sum of all angles divided by the sum of all lengths equals the agility factor with the unit [°/mm].




```
------ NC-Code ---------------------
N20 G1 X0 Y0 F=R1
N22 G91
N25 L_START
N30 G1 Y50 F=R3
N35 G1 X45
N40 G2 X60 Y35 I0 J-15
N45 G1 X60 Y20
N50 G3 X100 Y20 I20 J0
N55 G1 X100 Y50
N60 L_STOP
N70 M30
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$$W = \sum_{i=1}^{n} \frac{\delta_i}{l_i} \qquad \delta_i = \begin{matrix} \beta_i & (line, G1) \\ \beta_i + \gamma_i & (circle, G2/G3) \end{matrix} \qquad l_i = \begin{matrix} \sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2} & (line, G1) \\ \frac{\pi \cdot r_i \cdot \gamma_i}{180°} & (circle, G2/G3) \end{matrix} \qquad \beta_i = |180° - \alpha_i|$$

Figure 1. Basis calculation direction to identify the agility

The agility has a unique value for every cutting-geometry. By scaling geometries with < 1 the agility raises, due to the resultant shorter overall length by constant angular sum. The value of the agility represents the "friendliness" of a geometry sequence in the face of machine structures. More angles changing on shorter moving length reduces the average path velocity due to limited dynamic values of machine axes (jerk, acceleration). Less angle changing enables more phases for moving with high constant velocity, without the necessity of acceleration.

The interrelationship between the average path velocity of a machine system and the agility considering the dynamic values can be used to evaluate the efficiency of different cutting machines in a selected agility domain. For common cutting geometries, without any classification in thickness or industry sector, the median agility is given by approximately 4°/mm (figure 4).

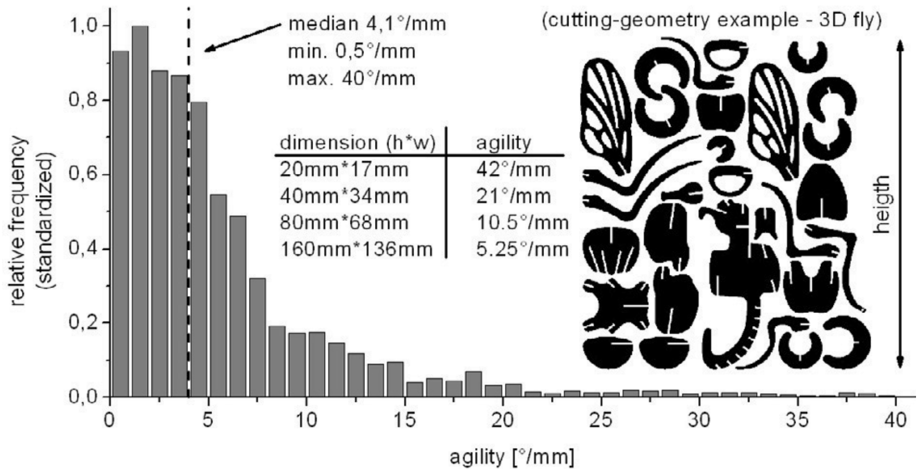

Figure 2. agility domain of typical cutting-geometries

For a time-dependent consideration of the agility, the mean path velocity can be observed as a function of the agility regarding to machine dynamics. Therefore the mean path velocities of two state of the art machines are shown in figure 3.

The deviation is dedicated by the use of different geometries at the same agility value for simulating the mean path velocity with jerk- and acceleration limitations. A different ratio in line- and circle amount, of contours with one and same agility is responsible for the deviations. A standard deviation of up to 10% has to be considered at this kind of observation.

The velocity level of machine 1 compared to machine 2 is constantly higher, due to a higher jerk value at comparable acceleration limits (see figure 3, dynamic values are shown in brackets). This reflects the importance of jerk in machine dynamics. The jerk as the time derivative of the acceleration is significant for axes systems to reach high velocity values also on short contour movements. To increase the mean velocity in the entire complexity domain, it is essential to overcome current jerk limitations of state of the art cutting machines. By comparing the dynamic constellations (acceleration and jerk) of cutting-machines in terms of reachable mean velocities, it is noticed that consistently the jerk is too low compared to the acceleration value [2]. At excessively low jerk values, the acceleration isn't capable to raise the mean velocity (see isoline figure 4). The jerk should be on a balanced level to the acceleration.

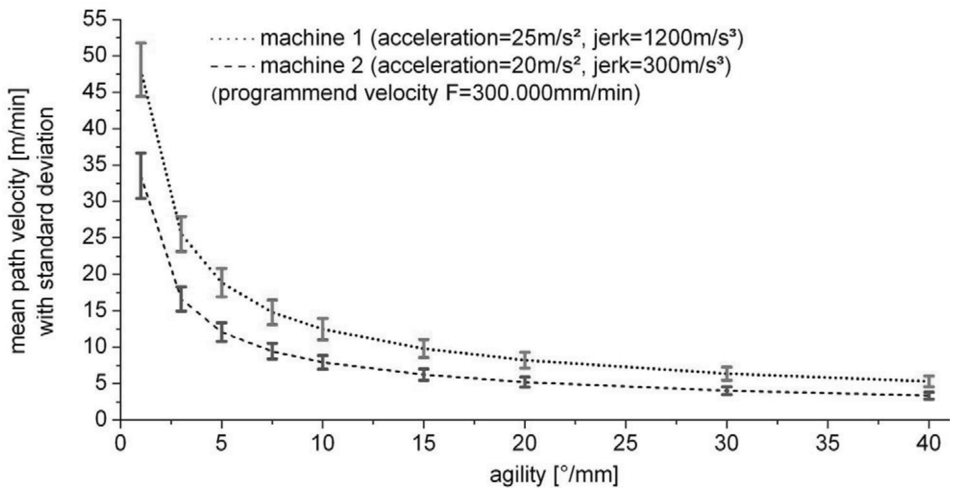

Figure 3. mean path velocity spread over a wide agility domain (for different dynamic values)

3. Application for dimensioning machine dynamics

The agility is a useful factor for dimensioning the dynamic values of machine axes. At the beginning it is required to define a median agility of the part-geometry domain for which the final machine should be designed for. With a part-geometry representing the median agility of the desired domain, an isoline graph of the mean velocity can be spread over jerk- and acceleration-limits. In figure 4 the isolines are shown for an agility of 4°/mm (compatible to the median agility of figure 2). Combinations of minimal jerk- and accelerations limits can be found for every isoline. Especially in areas with horizontal or vertical propagating isolines one of the dynamic-limitations are not fitting to each other. Most state of the art machines are located left of the optimum line. The mean velocity which should be reached by an axes system can be defined by technological limitations given by the beam source power, or by desired cycle-time for a part.

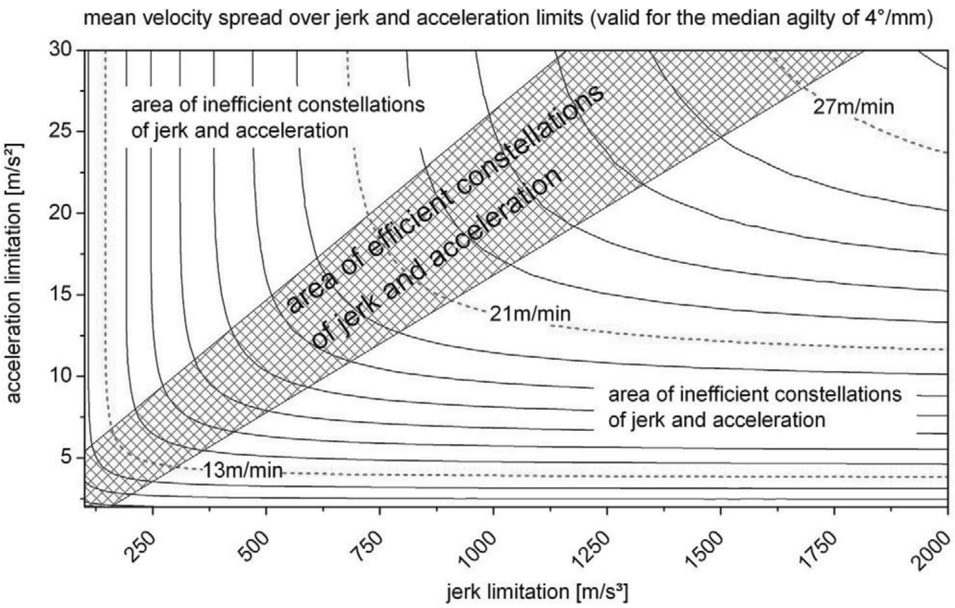

Figure 4. Mean velocity spread over jerk- an acceleration limitations (agility-working point at a median of 4°/mm)

If the technological velocity limit is the argument, a mean velocity of at least 70% of the technological velocity should be reached at the median agility of a chosen domain.

With this kind of graph a powerful tool is given to engineers to design machines whose dynamic values can fulfil the technological demands of laser-cutting with modern beam-sources.

The agility in general shows good and proven application opportunities for machine designers. In the future a uniform language could be spoken regarding the classification of the unlimited variety of cutting geometries.

Until this point, the velocity limitations by the process (dependent on laser power and material thickness) itself were not observed. The velocity was just limited by the machine axis. Figure 5 and figure 6 are the extension of figure 3 by observing typical cutting velocities in different material thicknesses. It can be seen, that the technological limitation has significant effect on the reachable mean velocity in the entire agility domain. Figure 5 shows a machine with low dynamics and figure 6 a machine with high dynamic values in jerk and acceleration. Both machines spread the dynamic-field of state of the art cutting machines. A lot of other machines where between this border-lines. In low cutting velocities the dynamic has just very low effect on the mean velocity (both machines are almost on the same level). The mean velocity is strongly affected by the positioning velocity which can be reached between cutting areas (programmed with 300.000mm/min). Due to this effect, the mean velocity can be higher then the limitations of the cutting process.

At high cutting velocities > 50m/min the increase of mean velocity is marginal. A cutting velocity of 100m/min has just low effect on the mean velocity compared with the mean velocity at 52m/min.

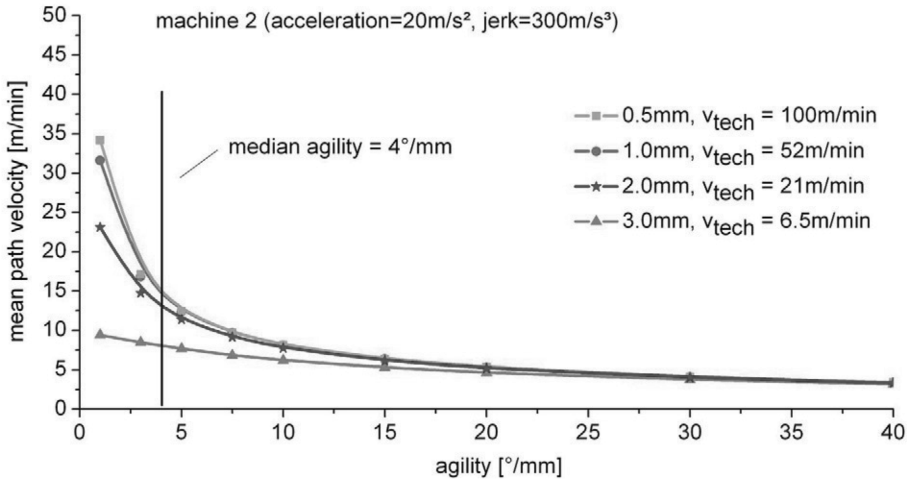

Figure 5. Mean velocity for a low dynamic machine (acceleration=20m/s², jerk=300m/s³)

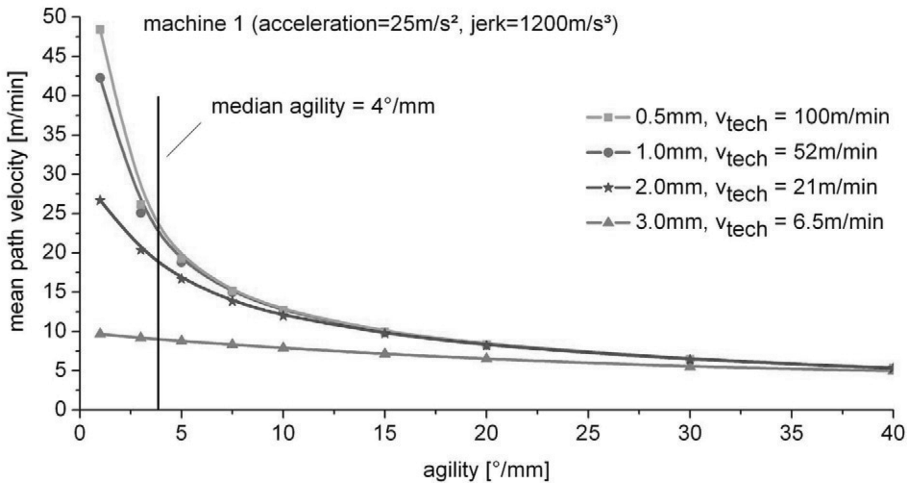

Figure 6. Mean velocity high dynamic machine (acceleration=25m/s², jerk=1200m/s³)

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